New Zealand Volcano Early Warning System (NZVEWS) Version 2: Monitoring Instrumentation Recommendations

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ABSTRACT

Over 10 years have passed since the last systematic review of Aotearoa New Zealand's volcano monitoring instrumentation requirements. Here, we conduct a new review, following and expanding on the approach taken by Miller (2011) and Miller and Jolly (2014) in the first New Zealand Volcano Early Warning System (NZVEWS) report.

In this report, we present recommendations on volcano monitoring instrumentation and a set of prioritisation principles to support their implementation for the next decade to 2033. Our recommendations are derived from a mixture of the United States Geological Survey National VEWS recommendations of Moran et al. (2008) and the data needs of the Aotearoa New Zealand volcano monitoring community, gathered from written submissions, a series of workshops and continued dialogue with the expert data users.

We group recommendations into four instrumentation levels and associate these levels with the volcano threat groups in Miller et al. (2022). We then compare the recommended and existing data acquisition networks to identify gaps. We invited the volcano monitoring community to design instrumentation networks that would address these gaps and align with the network design principles developed through data needs consultation. From these network designs, we produce minimum and maximum network recommendations for each volcano.

In total, 307 additional instrumentation stations are recommended in network designs and between 318 and 550 additional sensors are recommended overall (not including web cameras). To help guide the implementation of the recommendations over the next 10 years, we provide a set of prioritisation principles that have been agreed on by the GeoNet Volcano Monitoring Group at GNS Science.

KEYWORDS

volcano, threat, Aotearoa New Zealand, data, acquisition, instrumentation, processing, collection, monitoring, GeoNet

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1.0 INTRODUCTION

The first version of the New Zealand Volcano Early Warning System (NZVEWS; Miller 2011; Miller and Jolly 2014) produced a review of Aotearoa New Zealand's volcano monitoring instrumentation and compared these with the United States Geological Survey (USGS) National VEWS (NVEWS) recommendations for threat-appropriate volcano monitoring (Moran et al. 2008). NZVEWS concluded with recommendations for expanding data acquisition at those volcanoes where the capability fell short of threat-appropriate levels.

With more than a decade having passed since the first version of NZVEWS, it is timely to review volcano monitoring instrumentation requirements for Aotearoa New Zealand's monitored volcanoes (Figure 1.1) to ensure that they support current best practise and are appropriate for revised volcano threat rankings. Here, we focus on the instrumentation and data provision aspect of early warning, ensuring that there is adequate data to support early warning systems (Tupper and Leonard 2023). Consideration of full early warning to the end user is not part of this report. This work is also aligned to United Nations recommendations that everyone on Earth should be protected by early warning systems.[1]

Miller et al. (2022) produced updated threat scores and threat groupings for Aotearoa New Zealand's volcanoes, revising the work of Miller (2011) and Miller and Jolly (2014). Volcano threat in NZVEWS is approximated by the product of volcanic hazard and the exposure of people and property to that hazard, and volcanoes are grouped by the 33rd and 66th percentages of the maximum threat score (Table 1.1). The threat scores of Miller et al. (2022) are relative rankings only and do not reflect the quantitative risk associated with the volcanoes.

In the USGS NVEWS instrumentation recommendations (Moran et al. 2008), volcanoes are assigned recommended levels of instrumentation according to their threat group. These recommendations are divided by the instrumentation and data acquisition needs of the main volcano monitoring disciplines: seismology/acoustics, geodesy, geochemistry/ environmental and remote sensing. Different threat levels require different levels of instrumentation. We recognise that the USGS recommendations are now 15 years old and, while the principles of monitoring remain the same, the specific technologies used to achieve those principles are out of date. Here, we use the USGS principles as the foundations of requirements; however, they are updated through consultation with the Aotearoa New Zealand volcano community to reflect current best practise.

1 https://unfccc.int/news/un-early-warning-systems-must-protect-everyone-within-five-years

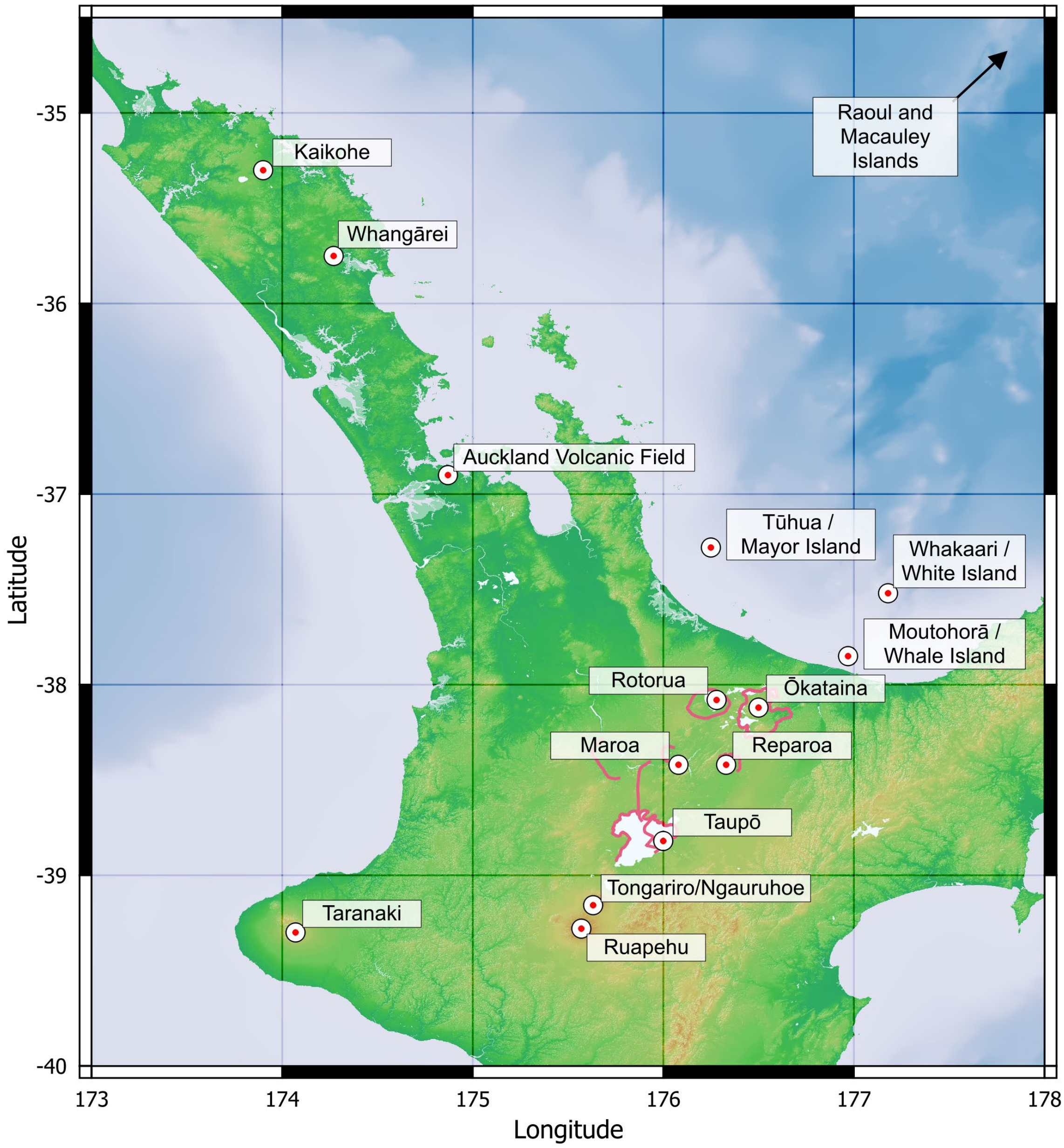

Figure 1.1 Map of the monitored Aotearoa New Zealand volcanoes, with caldera boundaries shown as pink lines (Heron 2018). Topographic data are sourced from the Land Information New Zealand Data Service. Crown Copyright Reserved; contains information licensed under the National Institute of Water & Atmospheric Research Open Data Licence v1.0.

In Aotearoa New Zealand, volcano monitoring is undertaken by GNS Science through the GeoNet programme, primarily via the Volcano Monitoring Group (VMG), in collaboration with external Aotearoa New Zealand universities through the New Zealand Volcano Science Advisory Panel (NZVSAP). GeoNet commissions and operates the automatic data acquisition, transportation networks and collection of the data, which supply the bulk of volcano monitoring data in Aotearoa New Zealand; as well as fund manual data acquisition and processing. The VMG are GNS Science staff who supply expert analysis, judgement and interpretation of the monitoring data and includes the National Geohazards Monitoring Centre.

Table 1.1 Threat groups of volcanoes and associated recommended level of instrumentation and data acquisition, in order of threat score from Miller et al. (2022).

Volcano	Threat Group	Instrumentation and Data Acquisition Level
Ōkataina	High	4
Auckland Volcanic Field	High	4
Taranaki	High	4
Ruapehu	High	4
Taupō	High	4
Tongariro/Ngauruhoe	High	4
Rotorua	Medium	3
Whakaari (White Island)	Medium	3
Maroa	Medium	3
Reporoa	Medium	3
Raoul Island	Low/Medium	2
Tūhua (Mayor Island)	Low/Medium	2
Moutohorā (Whale Island)	Low/Medium	2
Kaikohe / Bay of Islands	Low	1
Whangārei	Low	1
Macauley Island	Low	1

In this report, we synthesise the results of consultation with the Aotearoa New Zealand volcano monitoring community (scientists and technicians from GNS Science and Aotearoa New Zealand universities) on their volcano monitoring data needs for the next decade and use these to produce threat-appropriate data acquisition and processing recommendations.

We recommend specific network designs for both geophysical and geochemical techniques, including minimum and maximum instrumentation requirements and network design principles. In addition, we make recommendations across other data types used for volcano monitoring in Aotearoa New Zealand. We also suggest novel or stretch monitoring goals, where appropriate. A glossary of terms used throughout this report is available in Appendix 1.

2.0 METHODS

2.1 Volcano Monitoring Instrumentation, Data Acquisition and Processing Needs Consultation

To understand the data needs for Aotearoa New Zealand's volcano monitoring, we undertook a two-stage workshop-style consultation with Aotearoa New Zealand's volcano monitoring community. In the first stage, we asked participants to provide written submissions in the form of 'user stories', comprised of four clauses, describing their use of data:

1. 'As a (specific type of volcano scientist) ...'
2. 'I want to be able to ...'
3. 'So that I can ...'
4. 'To do this I need …'

Participants were encouraged to provide details for the user story's fourth clause as:

1. The number of data acquisition locations required.
2. The distance from a volcano that these should be within (or up-wind/down-wind, etc.).
3. The sampling characteristics of the data acquisition.
4. Whether this need relates to all volcanoes, a subset thereof, or a single volcano.

Anonymised user stories are provided in Appendix 3. Participants were asked to provide as many user stories as needed to capture the full range of their volcano monitoring data needs. Forty-eight written submissions were received covering the data needs for multiple aspects of volcano monitoring.

In the second stage of consultation, we invited participants to a series of discussions where we explored the data acquisition and processing needs of related disciplines in an unstructured but facilitated format. The workshops were attended by 27 people, covering seismology, geodesy, geochemistry and remote sensing disciplines.

2.2 Recommendation Design

From the consultation outputs, we grouped user stories by generalised aim, for example, earthquake characterisation, eruption detection, deformation source modelling, gas geochemistry, etc. (see Section 3 for all monitoring aims). By aggregating needs within each aim, we identified the set of data acquisition and processing requirements necessary for each aim's realisation.

We compared these requirements with the principles and recommendations of Moran et al. (2008) and found that they were compatible across the range of instrumentation and data acquisition levels. We then modified the USGS NVEWS recommendations to reflect the Aotearoa New Zealand volcano science community's needs, resulting in a hybrid recommendation design tailored for Aotearoa New Zealand volcano monitoring.

To map the volcano threat-level groups of Miller et al. (2022) to the four instrumentation levels of Moran et al. (2008), we set our high threat volcanoes as requiring instrumentation Level 4, medium threat volcanoes as requiring instrumentation Level 3 and low threat volcanoes as requiring instrumentation Level 1 (Table 1.1). We map Raoul Island, Tūhua (Mayor Island) and Moutohorā (Whale Island) volcanoes, which are close to the low/medium threat boundary in Miller et al. (2022), to instrumentation Level 2 (Table 1.1).

Recommended instrument numbers are presented in Table 3.1. We present instrument numbers as both totals and numbers within distances from the volcano. In some cases, instrument numbers are presented as ranges, where the smaller number is the minimum required and the larger number is the preferred number to meet the needs of expert data users.

2.3 Volcano Monitoring Network Design Consultation

To turn general instrumentation and data acquisition recommendations into specific network recommendations for each volcano, we invited subgroups of discipline experts to propose instrument locations around each volcano in line with the NZVEWS instrumentation recommendations and network design principles.

We focused this map-based network design exercise on seismometers, infrasound, GNSS (Global Navigation Satellite System), DOAS (Differential Optical Absorption Spectroscopy), MultiGAS sensors and LRDCP (Low-Rate Data Collection Platform) stations, which form the core of the continuous instrumentation networks operated by GeoNet and used by the expert community for volcano monitoring.

Because many of Aotearoa New Zealand’s volcanoes are closely spaced, we prompted respondents to design networks whose data could be used to monitor adjacent volcanoes where possible. We also promoted the co-location of multiple instrument types at single locations, both for logistical and economic benefits and for the added scientific value of coincident datasets (which was strongly emphasised in consultation).

Flexibility in adhering strictly to the recommendations was given for cases such as island volcanoes, where available land area limits the instrumentation. Recommendations for certain lake or marine instrumentation are included in the Novel Instrumentation and Stretch Goals section (Section 3.5).

2.4 Network Syntheses

Starting from the existing GeoNet network and using the NZVEWS instrumentation recommendations and network design principles (Section 3), we designed networks for each volcano from the instrument locations proposed by respondents. We co-located instruments whenever the locations of different instruments were close together. Some proposed locations were also relocated to account for known physical constraints (e.g. forestry) and cultural sensitivities. This was not possible in all cases, such as at Ōkataina, where forestry covers most of the volcano and surrounding region. In most cases, we selected instrument locations up to maximum NZVEWS recommendations but highlighted locations for the minimum recommendations also.

3.0 RECOMMENDATIONS

The vision for data acquisition is to have adequate instrumentation in place so that, when a geohazard event occurs, minimal additional data acquisition is required. As such, we make no recommendation for response-specific instrument caches or manual data acquisition and instead focus more on which instrument networks would achieve sufficient data for both volcano monitoring and event response. Similarly, our recommendations reflect minimum instrumentation required for volcano monitoring and response and should not preclude instrumentation efforts greater than those recommended.

Table 3.1 provides a summary of the recommendations. In some cases, recommendations are dependent on the type of volcano (e.g. cone volcanoes versus caldera and field volcanoes; for definitions, see Appendix 1) or the type of baseline activity (e.g. degassing through a plume).

In each following subsection, we outline the monitoring aims, network design principles and instrumentation requirements for each monitoring discipline. Recommendations about instrumentation technology (rather than counts or densities) are only made regarding changes to current GeoNet capabilities.

Table 3.1 Summary of instrumentation recommendations.

<table>
<tr><th></th><th>Level 1</th><th>Level 2</th><th>Level 3</th><th>Level 4</th></tr>
<tr><td>Seismic and Infrasound</td><td>• Five seismic stations within 200 km, including two within 50 km.
• No infrasound.</td><td>• Five seismic stations within 50 km, including two within 10 km.
• No infrasound.</td><td>• 6–10 seismic stations within 20 km, with at least one broadband station within 5 km.
• At cone volcanoes, 3–5 single infrasound sensors co-located with seismic stations.</td><td>• 12–20 seismic stations within 20 km, with at least six broadband seismic stations within 5 km.
• At least one co-located strong motion station within 5 km.
• At least one co-located infrasound sensor with each seismic station.
• At cone volcanoes, 3–4 seismic stations within 15–20 km of the volcano co-located with infrasound arrays.
• At caldera and field volcanoes, 2–3 seismic stations within 15–20 km of the volcano co-located with infrasound arrays.</td></tr>
<tr><td>Geodetic</td><td>Quarterly InSAR.</td><td>• Quarterly InSAR.
• One continuous-mode GNSS station within 10 km.</td><td>• Monthly InSAR.
• Annual campaign gravity.
• 7–10 continuous-mode GNSS stations, of which 3–4 are within 5 km.</td><td>• InSAR at the highest rate available from the satellite.
• Annual campaign gravity.
• One continuous absolute gravity measurement near volcanic centre.
• 16–20 continuous-mode GNSS stations, with 3–4 within 5 km and 10 within 10 km.</td></tr>
<tr><td>Geochemistry Environmental</td><td>Nil.</td><td>• Annual sampling and chemical analysis of gases/water of appropriate features.
• Continuous measurements (e.g. temperature, water level) of appropriate features.</td><td colspan="2">All Level 3+ volcanoes:
• Annual to monthly sampling and chemical analysis of gas/water from appropriate features.
• Continuous chemical composition (e.g. MultiGAS) and temperature measurements of appropriate features.
• Annual campaign soil/lake CO_2 flux survey.
Volcanoes that also create gas plumes:
• 4–7 DOAS and/or UV camera stations within 4–7 km of the vents, covering all wind directions.
• 3–4 MultiGAS stations around crater edges, covering all wind directions.
• Monthly airborne multi-species gas surveys.
• Monthly acquisition and chemical analysis of aerosols.</td></tr>
<tr><td>Remote Sensing</td><td>• Annual acquisition of thermal anomaly imagery.
• LiDAR basemap.</td><td>Same as for Level 1.</td><td>• Quarterly acquisition of thermal anomaly imagery.
• LiDAR basemap.
Volcanoes that also create gas plumes:
• Level 4 recommendations apply.</td><td>• Quarterly acquisition of thermal anomaly imagery.
• LiDAR basemap.
• 3–4 webcams per active volcano, capturing multiple vent angles and fields of view.
• Daily near-real-time TropOMI SO_2 imagery.</td></tr>
</table>

3.1 Seismic and Infrasound Monitoring

Seismic and infrasound (acoustic) monitoring are combined, as they provide complementary data streams and are often collected using a common digitiser at a station. The goals of seismic and infrasound monitoring are to:

- Detect, accurately locate and compute magnitudes and source properties of tectonic earthquakes near volcanoes to magnitude M1.
- Detect and analyse low-frequency earthquakes and tremor.
- Monitor for changes in seismic velocity.
- Monitor for lahars.
- Detect and locate volcanic explosions.
- Locate the source of volcanic eruptions in the case of multi-vent volcanoes, such as Tongariro or the Auckland Volcanic Field.

3.1.1 Design Principles

In all cases, focus stations (both seismic and infrasound) should be located within 5 km of volcanic vent areas, with azimuthal coverage gaps less than 45° of all significant sources in the volcanic region. Where possible, co-locate seismic and infrasound sensors. For seismometers, secure as many inter-station ray paths as can intersect likely regions of volcanic activity in the network geometry, and, for caldera volcanoes and volcanic fields, have some sensors installed up to 10 km outside of the caldera/field margin.

3.1.2 Number of Instruments

Level 1 Volcanoes

- Five seismic stations within 200 km, including two within 50 km.
- No infrasound.

Level 2 Volcanoes

- Five seismic stations within 50 km, including two within 10 km.
- No infrasound.

Level 3 Volcanoes

- 6–10 seismic stations within 20 km, with at least one broadband station within 5 km.
- At cone volcanoes, 3–5 single infrasound sensors co-located with seismic stations.

Level 4 Volcanoes

- 12–20 seismic stations within 20 km, with at least six broadband seismic stations within 5 km.
- At least one co-located strong motion station within 5 km.
- At least one co-located infrasound sensor with each seismic station.
- At cone volcanoes, 3–4 seismic stations within 15–20 km of the volcano co-located with infrasound arrays.

- At caldera and field volcanoes, 2–3 seismic stations within 15–20 km of the volcano co-located with infrasound arrays.

3.1.3 Instrumentation

- All new seismic stations should have broadband sensors, and boreholes should be employed where surface noise levels are detrimental to data quality (e.g. in urban or highly exposed areas).
- All new acoustic sensors should have differential pressure sensors with a flat response at >0.01 Hz. Strategies to reduce wind noise should be employed.
- Infrasound arrays should be built as a grouping of ≥3 sensors with common digitising and <200 m aperture.

3.2 Geodetic Monitoring

The goals of geodetic monitoring are to:

- Detect and accurately model sources of ground deformation.
- Detect the presence of ash in volcanic plumes.
- Measure mass fluxes and volume changes within volcanoes.

3.2.1 Design Principles

For volcanoes at instrumentation and data acquisition Levels 3 and 4, some stations should be closer to the volcano vent area (<5 km distance) and others more distal in the region around the vent (~5–15 km distance). Azimuthal gaps should be kept less than 45° around all significant deformation sources in the volcanic region, and it should be ensured that GNSS station distribution covers areas with poor InSAR coherence across the whole volcanic region where possible (i.e. not in water).

3.2.2 Numbers of Instruments and Data Acquisition Rate

Level 1 Volcanoes

- Quarterly InSAR.

Level 2 Volcanoes

- Quarterly InSAR.
- One continuous-mode GNSS station within 10 km.

Level 3 Volcanoes

- Monthly InSAR.
- Annual campaign gravity.
- 7–10 continuous-mode GNSS stations, with 3–4 within 5 km of the volcano.

Level 4 Volcanoes

- InSAR scene acquisition at the highest rate available from the satellite.
- Annual campaign gravity.

- One continuous absolute gravity measurement near the volcanic centre.
- 16–20 continuous-mode GNSS stations, with:
  - 3–4 within 5 km of the volcano, and
  - 10 within 10 km of the volcano.

3.3 Geochemical and Environmental Monitoring

The goals of geochemical and environmental monitoring are to:

- Quantify multi-species gas emissions, aerosol components and carbon isotope ratios in airborne plumes.
- Monitor temperature, water level and chemical composition of crater lakes, fumaroles, springs and/or bores.

3.3.1 Design Principles

Monitoring flux and composition of gas plumes (e.g. CO_2, SO_2, H_2S) and temperature, water level, and composition of appropriate features (e.g. fumaroles, springs, lakes, bores) should be the primary aim of data acquisition. Background values can be determined by measurements made at longer time intervals (e.g. monthly to yearly). However, during unrest this time interval should be shortened (e.g. weeks, days, or hours) depending on the instrumentation type and consideration given to automated instrumentation if possible.

3.3.2 Numbers of Instruments and Data Acquisition Rate

Level 1 Volcanoes

None.

Level 2 Volcanoes

- Annual manual sampling and chemical analysis of gases/water of appropriate features (fumaroles, springs, lakes, bores).
- Automated measurements (e.g. temperature, water level) of appropriate features (fumaroles, springs, lakes).

Level 3 and 4 Volcanoes

All Level 3+ volcanoes:

- Annual to monthly manual sampling and chemical analysis of gases/water of appropriate features (fumaroles, springs, lakes, bores).
- Automated chemical composition (e.g. MultiGAS) and temperature measurements of appropriate features (fumaroles, springs, lakes).
- Annual campaign soil/lake CO_2 flux survey for baseline characterisation.

For volcanoes that create gas plumes:

- 4–7 DOAS and/or UV camera stations within 4–7 km of the vents, covering all wind directions.
- 3–4 MultiGAS stations around crater edges, covering all wind directions.

- Monthly airborne multi-species gas surveys.
- Monthly acquisition and chemical analysis of aerosols.

3.3.3 Instrumentation

- In general, aim for higher acquisition rates (ideally continuous) that are automatic.
- Move toward near-real-time, continuous measurements of gas flux and composition (SO_2, CO_2, H_2S – e.g. DOAS/UV cameras + MultiGAS, continuous CO_2 flux sensors) that replace manual surveys where possible.
- Get near-real-time continuous measurements of temperature, water level and composition (e.g. through LRDCP) of appropriate features to supplement direct sampling and analysis of fluids.
- Aim to use unoccupied autonomous vehicles for manual sampling where possible.

3.4 Remote Sensing Monitoring

The goals of remote sensing for volcano monitoring are to:

- Map and quantify heat/thermal anomalies.
- Map and quantify SO_2 plumes.
- Make visual observations of volcanoes.
- Track volcano topography changes.

3.4.1 Numbers of Instruments and Data Acquisition Rate

Level 1 and 2 Volcanoes

- Annual acquisition of thermal anomaly imagery.
- LiDAR basemap.

Level 3 Volcanoes

- Quarterly acquisition of thermal anomaly imagery.
- LiDAR basemap.
- Volcanoes that create gas plumes: Level 4 recommendations apply.

Level 4 Volcanoes

- Quarterly acquisition of thermal anomaly imagery.
- LiDAR basemap.
- 3–4 webcams per active volcano, capturing multiple vent angles and fields of view.
- Daily near-real-time TropOMI SO_2 imagery.

3.4.2 Instrumentation and Data

Thermal cameras should be considered in some locations to monitor changes in vent, plume or fumarole temperatures and to support eruption confirmation. With advances in camera technology and telemetry capability, higher temporal rate and image resolution should be pursued.

3.5 Novel Instrumentation and Stretch Goals

A watching brief should be kept on evolving sensing technologies and the ability to implement test beds of novel instrumentation established. Technological developments in the following areas may open new opportunities for novel monitoring:

- Distributed Acoustic Sensing (DAS) using optical fibres around volcanic areas of interest. Use of dark fibre or dual-purpose fibre may allow rapid testing and uptake without the need for new fibre deployments.
- Telemetered ocean bottom seismometers for island and lake volcanoes to fill instrument azimuthal and distance from source gaps.
- Continuous absolute gravity measurements to track mass changes caused by fluid movement within the crust.
- Continuous electromagnetic monitoring of hydrothermal systems for changes in conductivity caused by fluid movements.
- Sampling gases from underwater vents (e.g. Ruapehu, Taupō).

4.0 RECOMMENDED NETWORK DESIGNS

In this section, we present the minimum and maximum recommended networks for infrasound, seismic, GNSS and geochemical and environmental monitoring. Table 4.1 presents the gap analysis of current and recommended monitoring instrumentation, and Figure 4.1 presents a visual summary of the gap analysis. Figures 4.2–4.7 present the minimum and maximum recommended networks for each volcano. No instrumentation Level 1 volcanoes (Table 1.1) are shown, as their current instrumentation is at or above recommended levels.

Table 4.1 Gap analyses for Aotearoa New Zealand volcanoes based on current/planned, minimum and maximum recommended instrumentation. Existing instrument counts are taken as those usually associated with monitoring a particular volcano. Slash dividers represent instrument counts measured from specific volcanic features within volcanoes, e.g. 'Tarawera/Makatiti' in Ōkataina. Dashes denote minimum versus maximum instrument counts and gaps. Abbreviations used in the table are: SP = short period seismometer; BB = broadband seismometer. Tongariro, Ruapehu and Whakaari (White Island) are all considered to create a gas plume. Taupō, Ōkataina, Maroa/Reporoa and Rotorua are caldera volcanoes. Tongariro/Ngauruhoe, Ruapehu, Taranaki and Whakaari (White Island) are cone volcanoes. Volcano instrumentation level is denoted by colour under the 'Level' column: red is Level 4, blue is Level 3; yellow is Level 2. Planned stations are considered as existing. Counts are valid as of October 2022.

Instrumentation Level	Volcano (Distance From)	Station Type	Number of Recommended Stations	Number of Existing Stations	Number of Additional Stations Required
4	Tongariro (Te Maari crater) / Ngauruhoe (summit)	Seismic <20 km	12–20	18 / 17	0–2 / 3
		Seismic <5 km	6BB	5 (2SP, 3BB) / 4 (3SP, 1BB)	3 / 5BB
		Infrasound array	3–4	0	3–4
		GNSS total	16–20	8–16	4–12
		GNSS <10 km	10	7 / 7	3
		GNSS <5 km	3–4	2 / 4	0 / 2
		DOAS	4–7	1	3–6
		MultiGAS (plume)	3–4	0	3–4
	Taupō (Horomatangi reef)	Seismic <20 km	12–20	7	5–13
		Seismic <5 km	6BB	0	6BB
		Infrasound array	2–3	0	2–3
		GNSS total	16–20	10	6–10
		GNSS <10 km	10	3	7
		GNSS <5 km	3–4	1	2–3
	Ruapehu (Te Wai ā-Moe crater lake)	Seismic <20 km	12–20	16	0–4
		Seismic <5 km	6BB	4 (4BB)	2BB
		Infrasound array	3–4	0	3–4
		GNSS total	16–20	8–16	4–12
		GNSS <10 km	10	6	4
		GNSS <5 km	3–4	4	0
		DOAS	4–7	2	2–5
		MultiGAS (plume)	3–4	0	3–4
	Taranaki (summit)	Seismic <20 km	12–20	8	4–12
		Seismic <5 km	6BB	2 (1SP, 1BB)	5BB

Instrumentation Level	Volcano (Distance From)	Station Type	Number of Recommended Stations	Number of Existing Stations	Number of Additional Stations Required
4	Taranaki (summit)	Infrasound array	3–4	0	3–4
		GNSS total	16–20	3	13–17
		GNSS <10 km	10	2	8
		GNSS <5 km	3–4	2	1–2
	Auckland Volcanic Field (Rangitoto / South Auckland)	Seismic <20 km	12–20	5	7–15
		Seismic <5 km	6BB	1SP / 0	6BB
		Infrasound array	2–3	0	2–3
		GNSS total	16–20	1	15–19
		GNSS <10 km	10	1 / 0	9 / 10
		GNSS <5 km	3–4	0 / 0	3–4
	Ōkataina (Tarawera/Makatiti)	Seismic <20 km	12–20	5 / 5	7–15
		Seismic <5 km	6BB	1 / 1 SP	6BB
		Infrasound array	2–3	0	2–3
		GNSS total	16–20	8–16	0–12
		GNSS <10 km	10	4 / 4	6
		GNSS <5 km	3–4	1 / 1	2–3
3	Maroa/Reporoa (Paeora fault)	Seismic <20 km	6–10	8	0–2
		Seismic <5 km	1BB	2SP	1BB
		GNSS total	7–10	6	1–4
		GNSS <5 km	3–4	2	1–2
	Whakaari (White Island) (crater)	Seismic <20 km	6–10	2	4–8
		Seismic <5 km	1BB	2BB	0
		GNSS total	7–10	2	5–8
		GNSS <5 km	3–4	2	1–2
		DOAS	4–7	0	4–7
		MultiGAS (plume)	3–4	0	3–4
	Rotorua (Mokoia Island)	Seismic <20 km	6–10	7	0–3
		Seismic <5 km	1BB	0 (3 SP <10 km)	1BB
		GNSS total	7–10	8–16	0
		GNSS < 5 km	3–4	0 (2 <10 km)	3–4
2	Moutohorā (Whale Island)	Seismic <50 km	5	7	0
		Seismic <10 km	2	1	1
		GNSS <10 km	1	0	1
	Tūhua (Mayor Island)	Seismic <50 km	5	2	3
		Seismic <10 km	2	1	1
		GNSS <10 km	1	0	1
	Raoul Island	Seismic <50 km	5	2	3
		Seismic <10 km	2	2	0
		GNSS <10 km	1	1	0

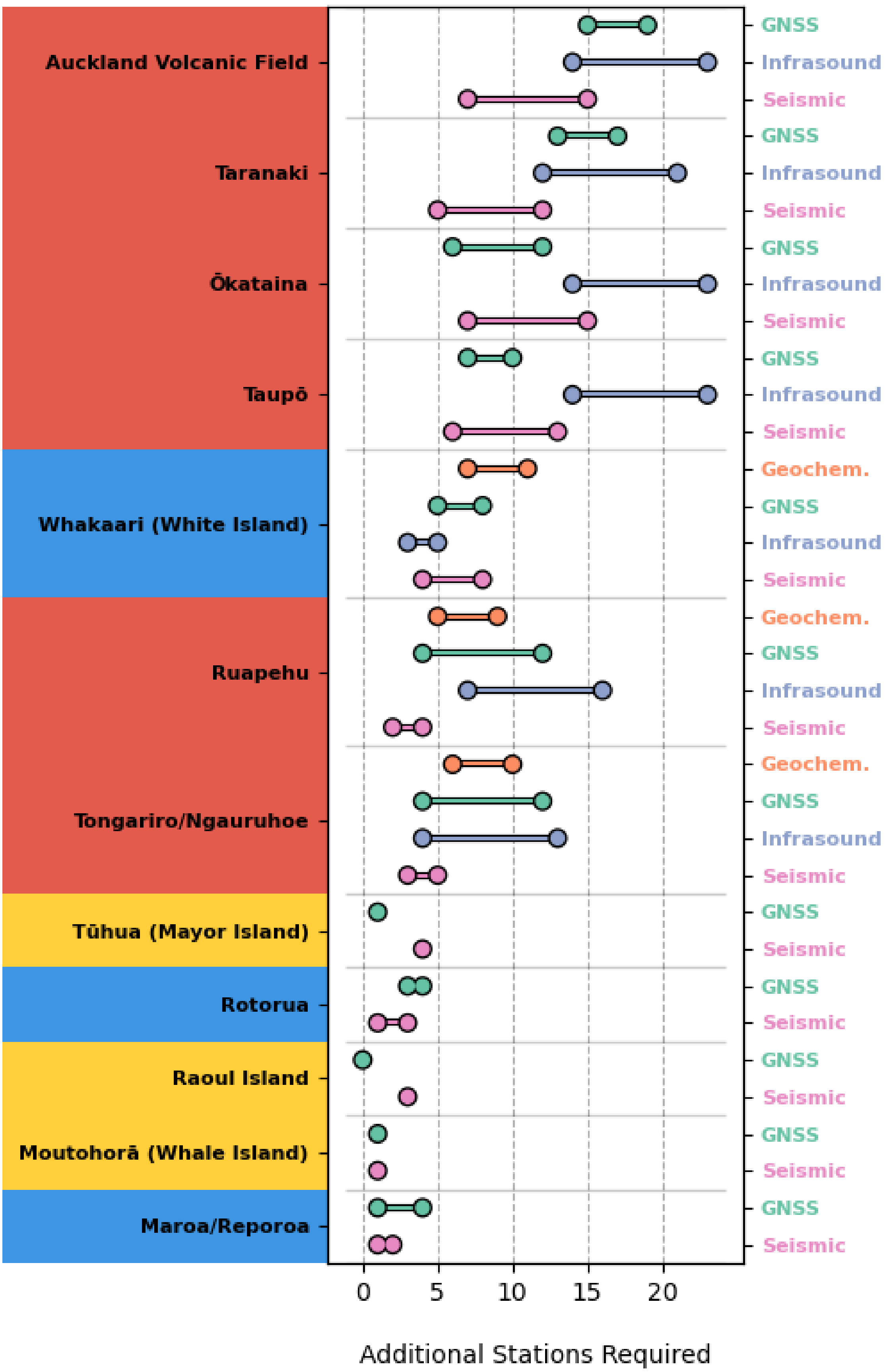

Figure 4.1 Number of total additional stations required at each volcano, as presented in Table 4.1 and ordered by decreasing mean instrument gap for the minimum instrumentation level (left-hand dots). Ranges indicate minimum to maximum gap range. Infrasound arrays are counted as one station. LRDCP and MultiGAS are presented under 'Geochem.'. Colour coding of volcano names in the left column reflects the instrumentation level: red is Level 4; yellow is Level 3; blue is Level 2. Planned stations are considered as existing. Counts are valid as of October 2022.

4.1 Network Maps

The following sections show recommended network maps for each volcano. Appendix 2 is a list of coordinates of each station for use in GIS mapping software. A digital file is available by request from the authors.

In these figures, existing GeoNet instrumentation is shown by empty symbols. When an NZVEWS recommended station is intended to co-locate with an existing GeoNet station, the GeoNet station will appear as an empty symbol over- or under-laid with the filled symbol indicative of the NZVEWS recommendation.

4.1.1 Auckland Volcanic Field

The recommended network for the Auckland Volcanic Field (Figure 4.2) has:

- Eight new seismic stations, with three new co-located infrasound sensors and one new co-located infrasound array.
- 14 new GNSS stations.

This will result in a monitoring network of:

- 19 seismic stations, with three co-located infrasound sensors and one co-located infrasound array.
- 15 GNSS stations.

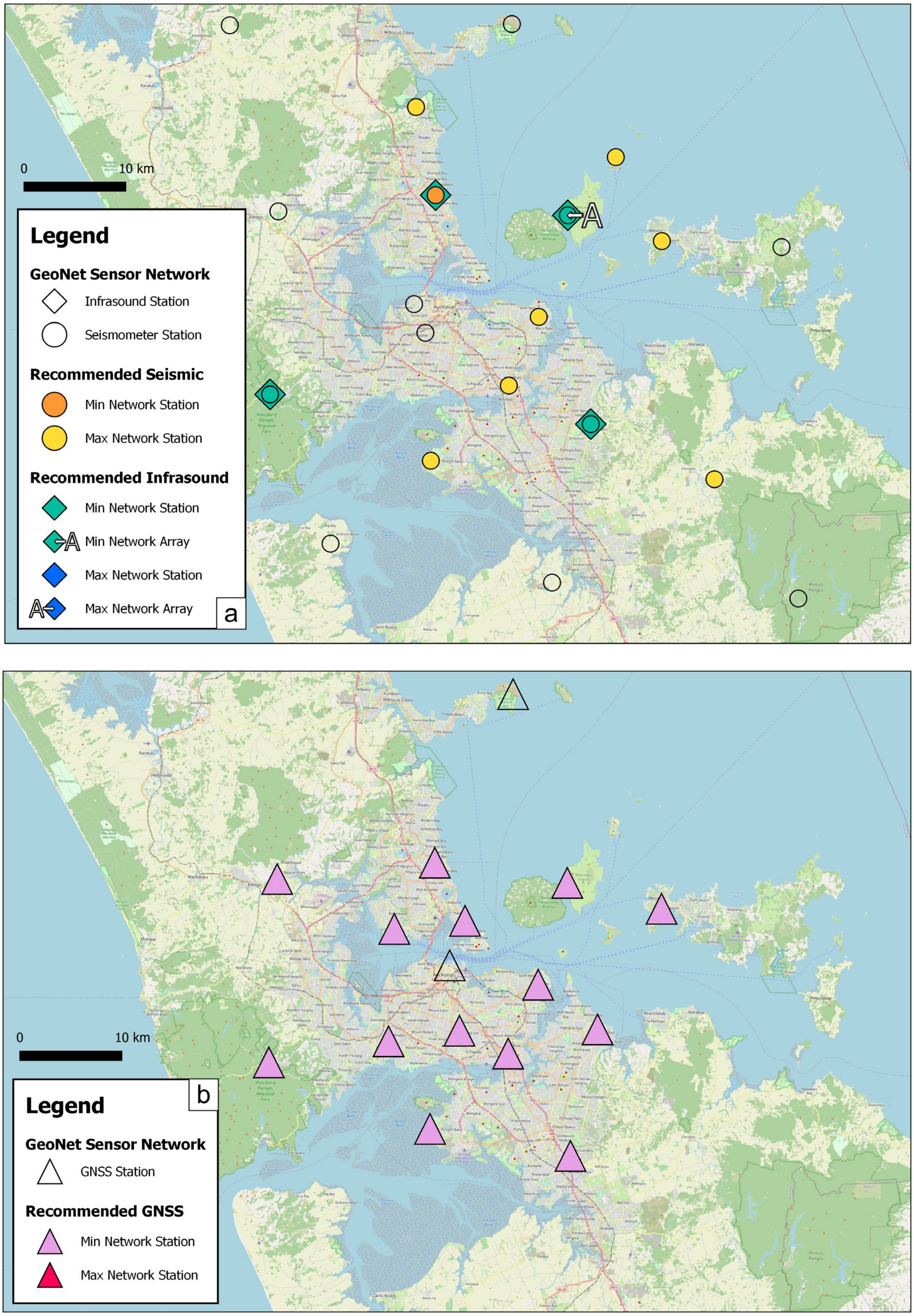

Figure 4.2 Auckland Volcanic Field recommended minimum and maximum data acquisition networks for (a) infrasound and seismic and (b) GNSS. Existing GeoNet sensor network stations are shown by unfilled symbols. Symbol overlaps indicate co-located stations.

4.1.2 Taranaki

The recommended network for Taranaki Volcano (Figure 4.3) has:

- 12 new seismic stations, with two new co-located infrasound sensors and two new co-located infrasound arrays.
- 13 new GNSS stations.

This will result in a monitoring network of:

- 20 seismic stations, with five co-located infrasound sensors and two co-located infrasound arrays.
- 16 GNSS stations.
- One LRDCP station.

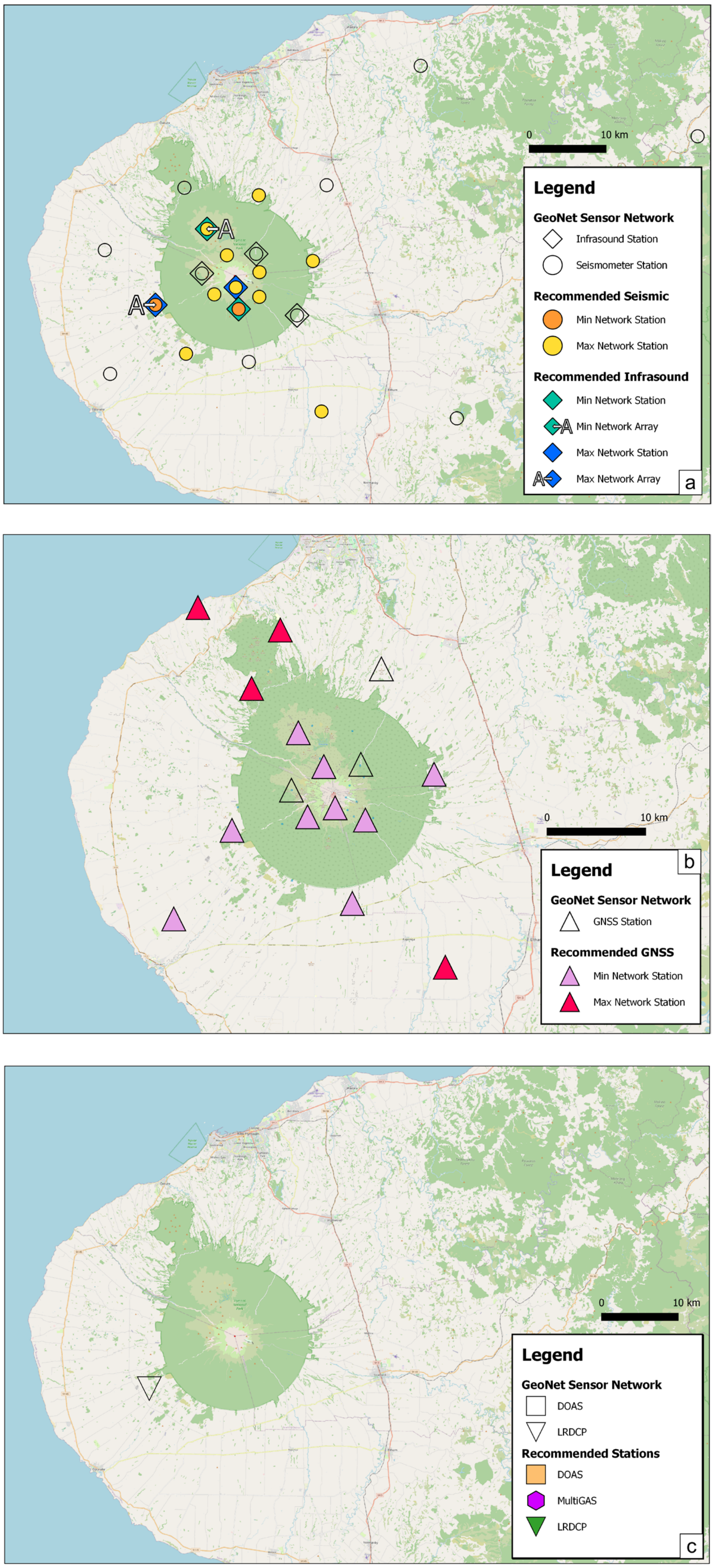

Figure 4.3 Taranaki Volcano recommended minimum and maximum data acquisition networks for (a) infrasound and seismic, (b) GNSS and (c) geochemical and environmental. Existing GeoNet sensor network stations are shown by unfilled symbols. Symbol overlaps indicate co-located stations. Exploration for features for manual sampling and LRDCP are needed in this region.

4.1.3 Ruapehu and Tongariro/Ngauruhoe

The recommended network for Ruapehu and Tongariro/Ngauruhoe Volcanoes (Figure 4.4) has:

- Eight new seismic stations, with three new co-located infrasound sensors, one new co-located infrasound array and three new stand-alone infrasound arrays.
- 10 new GNSS stations.
- Eight new DOAS stations.
- Five new MultiGAS stations.
- 10 new LRDCP stations.

This will result in a monitoring network of:

- 28 seismic stations, with 17 co-located infrasound sensors, one co-located infrasound arrays, and three stand-alone infrasound arrays.
- 26 GNSS stations.
- 13 DOAS stations.
- Five MultiGAS stations.
- 17 LRDCP stations.

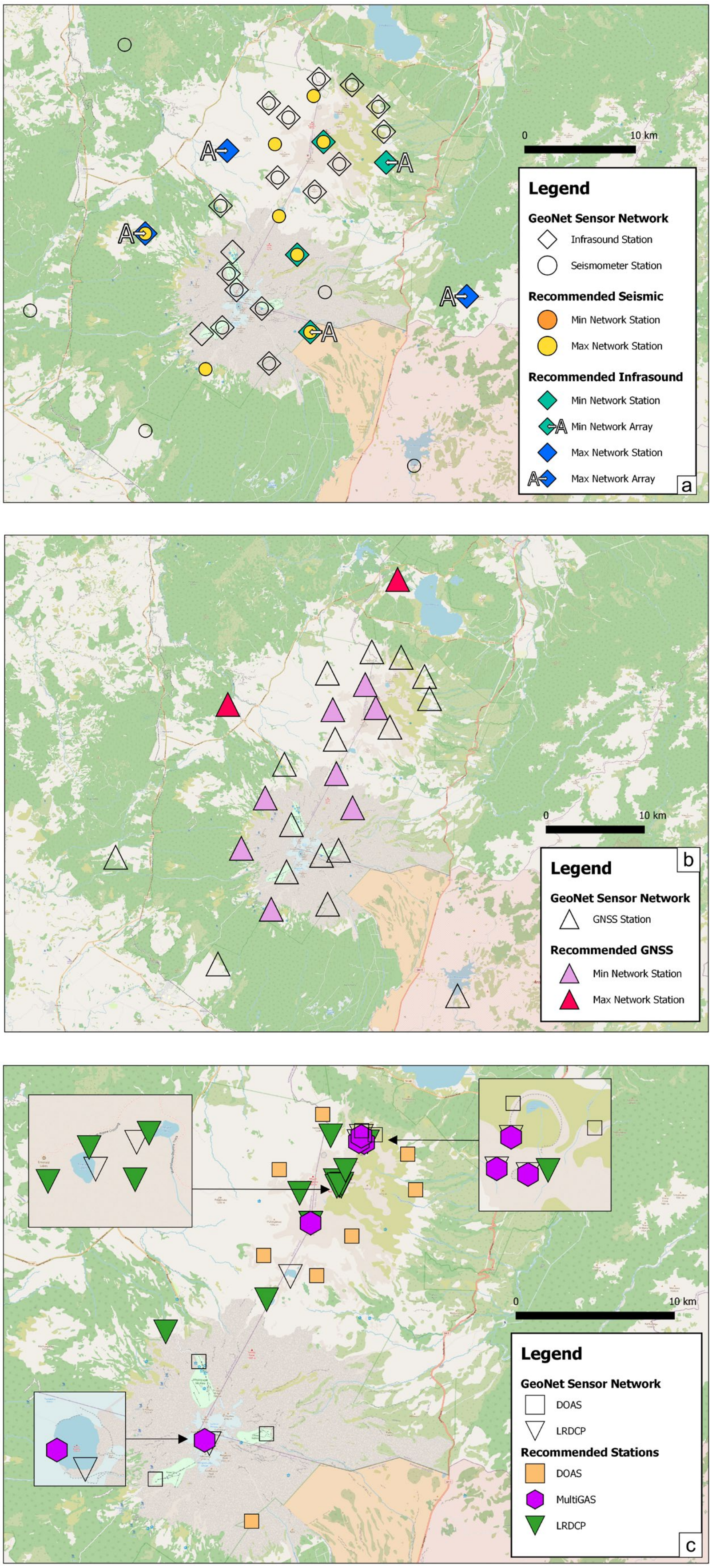

Figure 4.4 Ruapehu and Tongariro/Ngauruhoe volcanoes recommended minimum and maximum data acquisition networks for (a) infrasound and seismic, (b) GNSS and (c) geochemical and environmental. Existing GeoNet sensor network stations are shown by unfilled symbols. Symbol overlaps indicate co-located stations.

4.1.4 Taupō

The recommended network for Taupō Volcano (Figure 4.5) has:

- 12 new seismic stations, with four new co-located infrasound sensors and one new co-located infrasound array.
- Nine new GNSS stations.
- Three new LRDCP stations.

This will result in a monitoring network of:

- 19 seismic stations, with four co-located infrasound sensors and one co-located infrasound array.
- 19 GNSS stations.
- Three LRDCP stations.

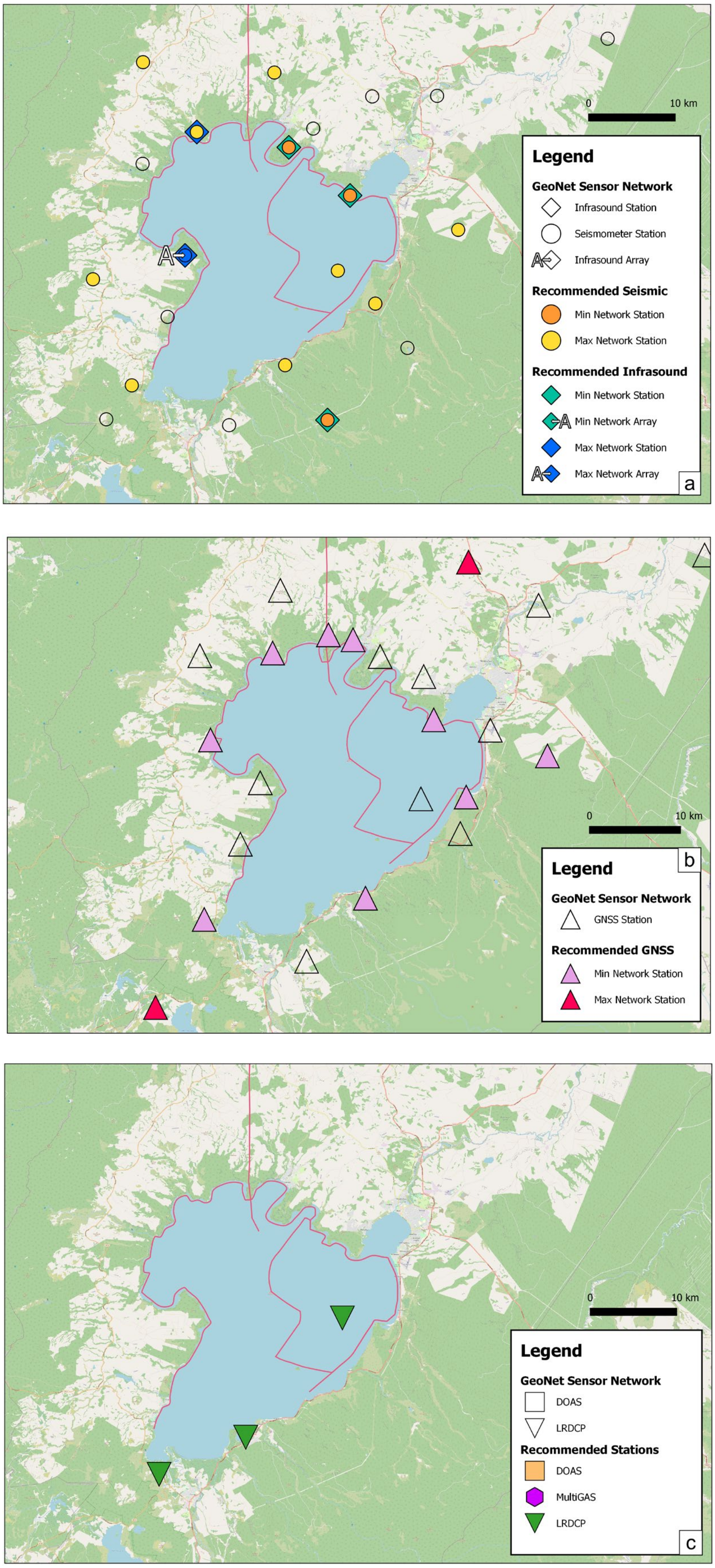

Figure 4.5 Taupō Volcano recommended minimum and maximum data acquisition networks for (a) infrasound and seismic, (b) GNSS and (c) geochemical and environmental. Existing GeoNet sensor network stations are shown by unfilled symbols. Symbol overlaps indicate co-located stations.

4.1.5 Rotorua and Ōkataina

The recommended network for Rotorua and Ōkataina Volcanoes (Figure 4.6) has:

- 23 new seismic stations, with eight new co-located infrasound sensors and two new stand-alone infrasound arrays.
- 14 new GNSS stations.
- Eight new LRDCP stations.

This will result in a monitoring network of:

- 33 seismic stations, with eight co-located infrasound sensors and two stand-alone infrasound arrays.
- 25 GNSS stations.
- 10 LRDCP stations.

4.1.6 Maroa and Reporoa

The recommended network for Maroa/Reporoa Volcanoes (Figure 4.6) has:

- Two new seismic stations.
- One new GNSS station.
- Four LRDCP stations.

This will result in a monitoring network of:

- Eight seismic stations.
- Three GNSS stations.
- Four LRDCP stations.

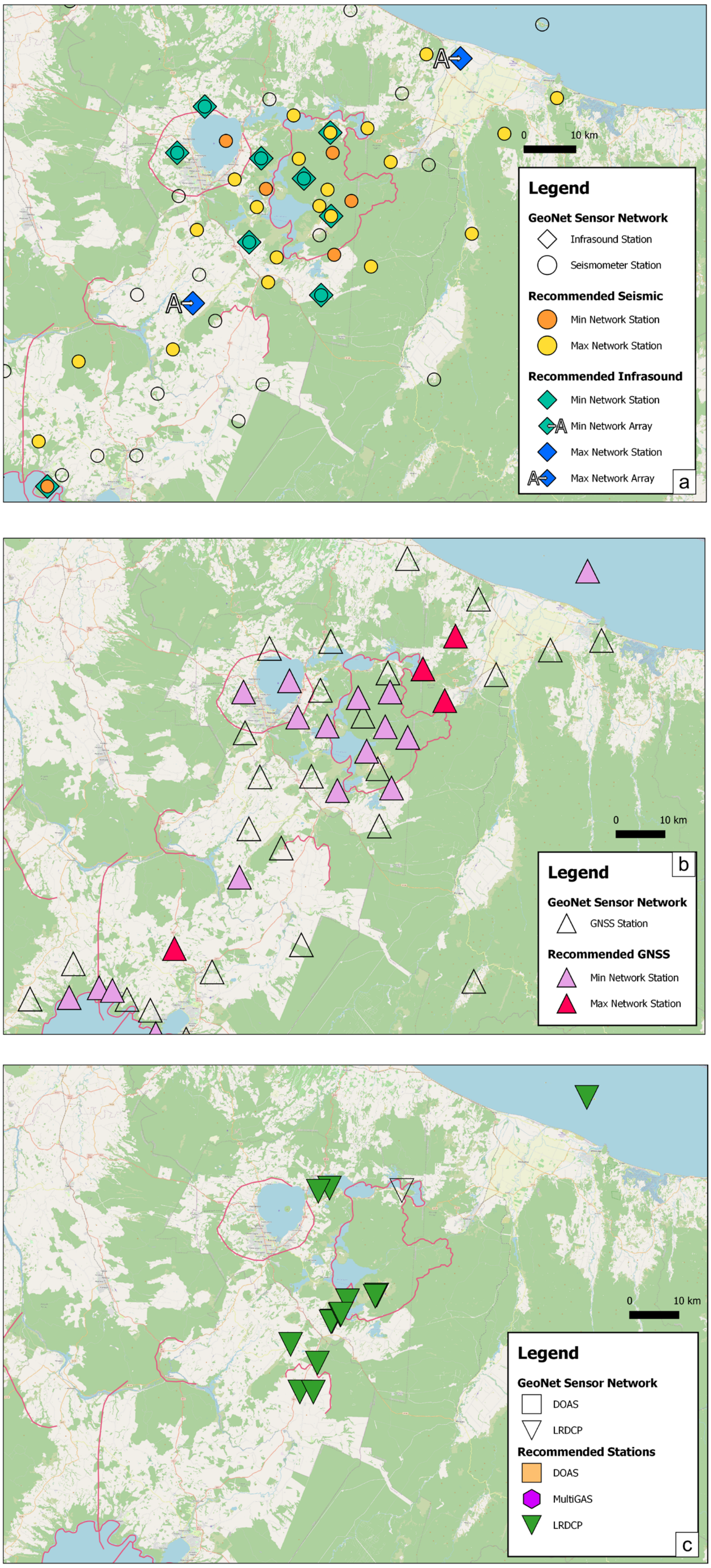

Figure 4.6 Maroa/Reporoa, Rotorua and Ōkataina recommended minimum and maximum data acquisition networks for (a) infrasound and seismic, (b) GNSS and (c) geochemical and environmental. Existing GeoNet sensor network stations are shown by unfilled symbols. Symbol overlaps indicate co-located stations.

4.1.7 Island Volcanoes

4.1.7.1 Whakaari (White Island)

The recommended network for Whakaari (White Island) (Figure 4.7) has:

- Four new seismic stations, with three new co-located infrasound sensors.
- Two new GNSS stations.
- Six new DOAS stations.
- Two new MultiGAS stations.
- Six new LRDCP stations.

This will result in a monitoring network of:

- Six seismic stations, with three co-located infrasound sensors and two co-located infrasound arrays.
- Four GNSS stations.
- Six DOAS stations.
- Two MultiGAS stations.
- Seven LRDCP stations.

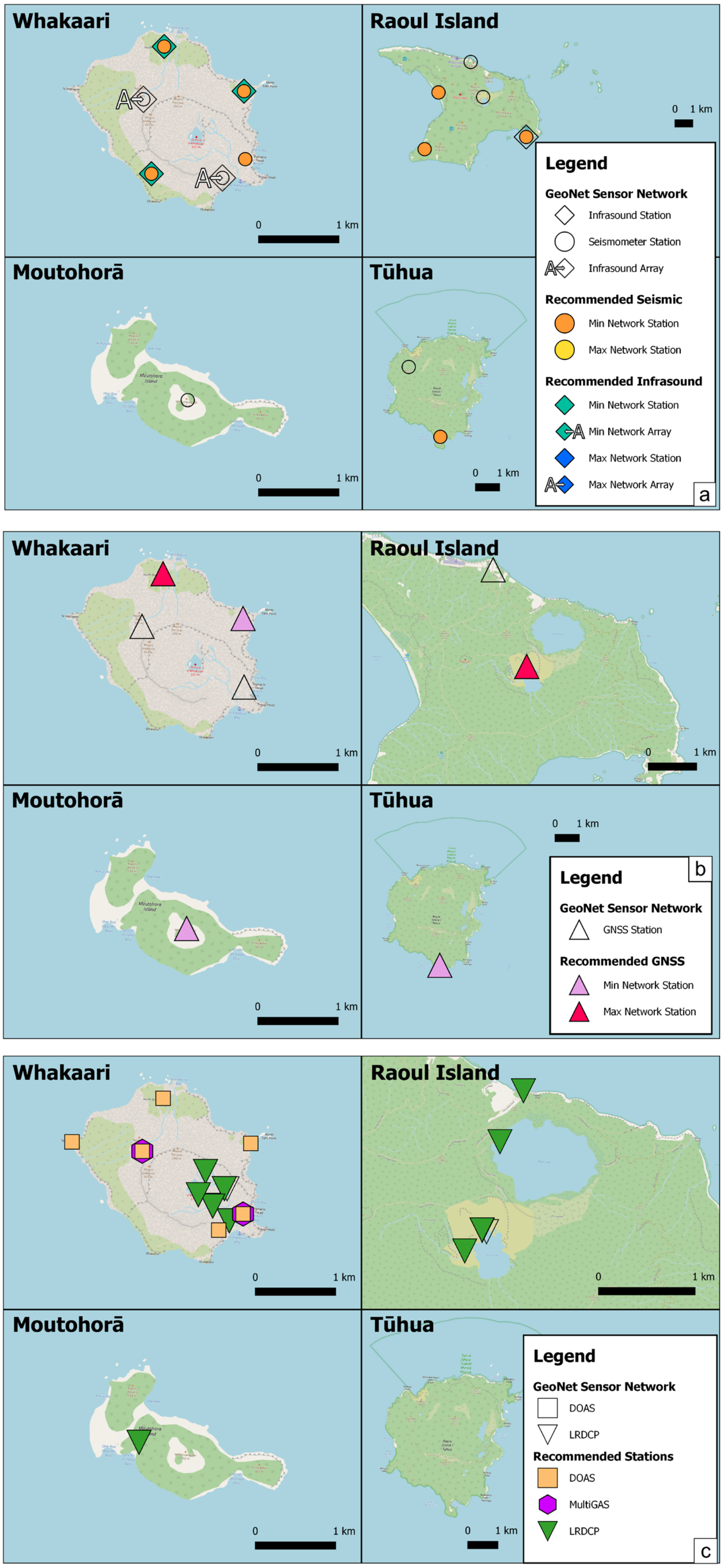

Figure 4.7 Island volcano recommended minimum and maximum data acquisition networks for (a) infrasound and seismic, (b) GNSS and (c) geochemical and environmental. In clockwise order from the top left: Whakaari (White Island), Raoul Island, Moutohorā (Whale Island), Tūhua (Mayor Island). Existing GeoNet sensor network stations are shown by unfilled symbols. Symbol overlaps indicate co-located stations. Recommended LRDCP stations are drawn from existing GeoNet geochemistry plans.

4.1.7.2 Raoul Island

The recommended network for Raoul Island (Figure 4.7) has:

- Three new seismic stations.
- One new GNSS station.
- Four new LRDCP stations.

This will result in a monitoring network of:

- Five seismic stations, with one co-located infrasound sensor.
- Two GNSS stations.
- Five LRDCP stations.

4.1.7.3 Moutohorā (Whale Island)

The recommended network for Moutohorā (Whale Island) (Figure 4.7) has:

- One new GNSS station.
- One new LRDCP station.

This will result in a monitoring network of:

- One seismic station.
- One GNSS station.
- One LRDCP station.

4.1.7.4 Tūhua (Mayor Island)

The recommended network for Tūhua (Mayor Island) (Figure 4.7) has:

- One new seismic station.
- One new GNSS station.

This will result in a monitoring network of:

- Two seismic stations.
- One GNSS station.

4.2 Prioritisation Recommendation

The NZVEWS recommendations are made with a 10-year view toward implementation. We expect that network upgrades will proceed incrementally over this period. To help ensure that each incremental network upgrade is the most valuable, we recommend prioritisation principles as follows:

1. Give priority to volcanoes with higher threat scores before those with lower threat scores.
2. Bring all networks up to minimum recommendations before working toward maximum recommendations.

For the recommendations presented in network maps (Figures 4.2–4.7), incremental network upgrades should look to locate stations as close as is feasible to the recommended locations.

Given that these recommendations set out a 10-year upgrade plan, it is possible that one or more volcanoes will undergo a period of unrest over this time window. In that case, it would be prudent to prioritise upgrade work to that volcano, independent of the prioritisation steps recommended above.

The prioritisation model requires some judgement to implement, and the order of priorities will change as recommendation implementation progresses. As such, we advise that yearly implementation roadmaps be developed and circulated among the expert data user and volcano monitoring communities for comment.

A straw-person prioritisation order is (based on Figure 4.1):

1. Auckland Volcanic Field
2. Taranaki
3. Ōkataina
4. Taupō
5. Ruapehu
6. Tongariro/Ngauruhoe
7. Whakaari (White Island)
8. Rotorua
9. Maroa/Reporoa
10. Tūhua (Mayor Island)
11. Raoul Island
12. Moutohorā (Whale Island).

4.3 Incremental Updates of NZVEWS Recommendations

We recommend that the next iteration of NZVEWS occurs no later than 2033. Our recommendations for the next 10 years do not preclude the introduction of new instrumentation or data acquisition methods as technology develops or as our understanding of what data are needed for threat-appropriate volcano monitoring evolves. A mechanism is required to allow for incremental changes to the recommendations ahead of the next full revision in 10 years' time. Should new unrest or an eruption occur in the next 10 years, it is recommended that that volcano's threat score be re-assessed and monitoring work re-prioritised accordingly.

5.0 CONCLUSIONS AND NEXT STEPS

This report provides recommendations for threat-appropriate volcano monitoring instrumentation and data acquisition out to 2033. The recommendations are grounded in the needs and understanding of the Aotearoa New Zealand volcano monitoring community and built upon a foundation of global best practise based on the USGS NVEWS (Moran et al. 2008) and earlier NZVEWS work (Miller 2011; Miller and Jolly 2014).

This report serves as a readily applicable instrumentation and network strategy and a reference for improving manual and remote-sensing data acquisition. Key next steps are:

- Secure long-term funding to support recommendation implementation.
- Develop an implementation roadmap that can be integrated with plans for other networks and data acquisition efforts.
- Implement these recommendations.

6.0 ACKNOWLEDGMENTS

We would like to acknowledge the CASCADE and GeoNet programmes at GNS Science for funding this work, the volcano monitoring community in Aotearoa New Zealand for their invaluable contributions; and OpenStreetMap, the GeoNet programme and GNS Science for the provision of geospatial data used in the maps throughout this report. Thanks also to Sigrún Hreinsdottir and Elizabeth Abbott for their review of this report.

Map data copyrighted by OpenStreetMap contributors and available from https://www.openstreetmap.org

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APPENDICES

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APPENDIX 1 GLOSSARY OF TERMS

Caldera volcanoes and volcanic fields	Large volcanic systems where the location of the next eruption is less well-constrained.
Cone volcanoes	Volcanoes with a single known vent from which eruptions are expected.
DOAS	Differential Optical Absorption Spectroscopy – used to quantify SO_2 emissions.
GNSS	Global Navigation Satellite System – shorthand for the system of satellites, ground control stations, antenna, receiver (etc.) that together provide data sufficient for millimetre-accurate ground-deformation measurements.
InSAR	Interferometric Synthetic Aperture Radar – used to map ground deformation .
LiDAR	Light Detection And Ranging – used to create detailed 3D terrain maps.
LRDCP	Low-Rate Data Capture Platform – a data collection platform for a range of sensors, e.g. temperature, MultiGAS.
MultiGAS	Measures the concentrations of SO_2, H_2S and CO_2 in gas.

APPENDIX 2 NETWORK STATION POSITIONS

List of longitude and latitude of all recommended stations shown in the network maps in Figures 4.2–4.7. Tabulated station positions are presented for seismic, infrasound, GNSS, DOAS, MultiGAS and LRDCP, respectively, in Tables A2.1–A2.6. Coordinates are presented to 0.01° (approximately 1 km) to reflect their indicative purpose.

Seismic Stations

Table A2.1 Locations of recommended seismic stations. 'P1' and 'P2' indicate minimum and maximum network recommendations, respectively.

Longitude	Latitude	Priority
173.94	-39.33	P1
174.07	-39.33	P1
175.92	-38.68	P1
176.00	-38.73	P1
175.98	-38.96	P1
176.38	-38.15	P1
176.52	-38.09	P1
176.57	-38.17	P1
176.53	-38.26	P1
176.29	-38.07	P1
176.25	-37.30	P1
177.19	-37.52	P1
177.19	-37.51	P1
177.18	-37.51	P1
177.17	-37.52	P1
-177.89	-29.28	P1
-177.94	-29.26	P1
-177.95	-29.29	P1
174.75	-36.75	P1
174.19	-39.45	P2
173.99	-39.38	P2
174.18	-39.27	P2
174.09	-39.20	P2
174.02	-39.24	P2
174.05	-39.27	P2

Longitude	Latitude	Priority
174.03	-39.31	P2
174.10	-39.32	P2
174.10	-39.29	P2
174.06	-39.31	P2
175.46	-39.22	P2
175.64	-39.30	P2
175.62	-39.23	P2
175.53	-39.33	P2
175.64	-39.14	P2
175.60	-39.20	P2
175.59	-39.14	P2
175.63	-39.10	P2
175.72	-38.93	P2
175.67	-38.82	P2
175.80	-38.67	P2
175.72	-38.60	P2
175.90	-38.60	P2
176.15	-38.76	P2
175.99	-38.81	P2
176.04	-38.84	P2
175.93	-38.91	P2
175.98	-38.46	P2
176.19	-38.44	P2
176.39	-38.32	P2
176.41	-38.27	P2

Longitude	Latitude	Priority
176.23	-38.23	P2
176.36	-38.19	P2
176.43	-38.03	P2
176.45	-38.10	P2
176.52	-38.05	P2
176.51	-38.15	P2
176.90	-38.04	P2
176.65	-38.10	P2
176.50	-38.18	P2
176.52	-38.20	P2
176.62	-38.28	P2
176.84	-38.22	P2
176.60	-38.04	P2
176.31	-38.14	P2
176.72	-37.91	P2
177.01	-37.98	P2
174.72	-36.67	P2
174.94	-36.71	P2
175.00	-36.79	P2
174.75	-36.98	P2
175.06	-37.00	P2
174.83	-36.92	P2
174.86	-36.85	P2

Infrasound Stations and Arrays

Table A2.2 Locations of recommended infrasound stations and arrays. 'P1' and 'P2' indicate minimum and maximum network recommendations, respectively. 'A' suffix indicates array.

Longitude	Latitude	Priority
174.07	-39.33	P1
175.62	-39.23	P1
175.64	-39.14	P1
175.92	-38.68	P1
176.00	-38.73	P1
175.98	-38.96	P1
176.35	-38.25	P1
176.52	-38.05	P1
176.46	-38.13	P1
176.52	-38.20	P1
176.51	-38.33	P1
176.37	-38.10	P1
176.24	-38.02	P1
176.18	-38.10	P1
177.19	-37.51	P1
177.18	-37.51	P1
177.17	-37.52	P1
174.57	-36.93	P1
174.75	-36.75	P1
174.92	-36.95	P1
174.02	-39.24	P1A
175.64	-39.30	P1A
175.7	-39.16	P1A
174.89	-36.76	P1A
174.06	-39.31	P2
175.79	-38.80	P2
175.80	-38.67	P2
173.94	-39.33	P2A
175.80	-39.26	P2A
175.46	-39.22	P2A
175.54	-39.15	P2A
175.80	-39.26	P2A
176.23	-38.36	P2A
176.79	-37.92	P2A

GNSS Stations

Table A2.3 Locations of recommended GNSS stations. 'P1' and 'P2' indicate minimum and maximum network recommendations, respectively.

Longitude	Latitude	Priority
173.87	-39.41	P1
173.94	-39.33	P1
174.02	-39.24	P1
174.05	-39.27	P1
174.03	-39.31	P1
174.10	-39.32	P1
174.06	-39.31	P1
175.62	-39.23	P1
175.53	-39.33	P1
175.49	-39.27	P1
175.52	-39.23	P1
175.64	-39.14	P1
175.60	-39.20	P1
175.59	-39.14	P1
175.63	-39.12	P1
175.72	-38.93	P1
175.72	-38.76	P1
175.80	-38.67	P1
175.87	-38.65	P1
175.90	-38.65	P1
176.00	-38.73	P1
176.15	-38.76	P1
176.05	-38.80	P1
175.93	-38.91	P1
176.19	-38.44	P1
176.41	-38.27	P1
176.38	-38.15	P1
176.45	-38.10	P1
176.52	-38.09	P1
176.51	-38.15	P1
176.57	-38.17	P1
176.47	-38.20	P1
176.53	-38.26	P1
176.31	-38.14	P1

Longitude	Latitude	Priority
176.18	-38.10	P1
176.29	-38.07	P1
176.97	-37.85	P1
176.25	-37.30	P1
177.19	-37.51	P1
174.57	-36.93	P1
174.57	-36.77	P1
174.75	-36.75	P1
174.89	-36.76	P1
174.75	-36.98	P1
174.90	-37.01	P1
174.93	-36.89	P1
174.83	-36.92	P1
174.86	-36.85	P1
174.70	-36.91	P1
174.78	-36.90	P1
174.70	-36.81	P1
174.78	-36.80	P1
174.08	-39.39	P1
174.18	-39.27	P1
175.00	-36.79	P1
174.19	-39.45	P2
173.99	-39.14	P2
173.90	-39.12	P2
175.47	-39.14	P2
175.66	-39.02	P2
176.04	-38.57	P2
176.65	-38.10	P2
176.67	-37.98	P2
176.60	-38.04	P2
177.18	-37.51	P2
-177.92	-29.26	P2
173.96	-39.20	P2

DOAS Stations

Table A2.4 Locations of recommended DOAS stations.

Longitude	Latitude
175.59	-39.32
175.64	-39.18
175.60	-39.17
175.61	-39.12
175.64	-39.09
175.70	-39.11
175.71	-39.13
175.66	-39.16
177.19	-37.52
177.18	-37.51
177.17	-37.51
177.16	-37.51
177.18	-37.52
177.19	-37.51

MultiGAS

Table A2.5 Locations of recommended MultiGAS stations.

Longitude	Latitude
175.56	-39.28
177.19	-37.52
177.17	-37.51
175.63	-39.15
175.67	-39.10
175.66	-39.10
175.66	-39.10

LRDCP Stations

Table A2.6 Locations of recommended LRDCP stations.

Longitude	Latitude
175.63	-39.15
176.50	-38.23
176.39	-38.28
176.41	-38.26
176.43	-38.24
176.36	-38.35
176.30	-38.32
176.38	-38.03
176.35	-38.04
176.41	-38.26
176.49	-38.23
176.33	-38.41
176.36	-38.41
175.53	-39.22
175.76	-38.96
175.87	-38.92
176	-38.8
175.65	-39.13
175.64	-39.10
175.65	-39.13
175.65	-39.13
175.67	-39.10
175.65	-39.13
175.65	-39.13
175.65	-39.12
175.62	-39.13
175.60	-39.20
177.19	-37.52
177.18	-37.52
177.18	-37.52
177.18	-37.52
177.18	-37.52
177.18	-37.52
176.96	-37.85
-177.92	-29.26
-177.91	-29.25
-177.91	-29.24
-177.92	-29.26

APPENDIX 3 USER STORIES

We received user stories and had participation from staff at several organisations: Te Herenga Waka Victoria University of Wellington, Waipapa Taumata Rau University of Auckland, Te Kunenga Ki Pūrehuroa Massey University and Te Pū Ao GNS Science. The majority of these are included in anonymised format in Table A3.1.

Table A3.1 Anonymised written submissions. Note that submissions from two participants are absent. Submissions have been minimally edited for clarity.

I Want to:	So that I Can:	To Do this I Need:
Detect, accurately locate and compute magnitudes and source properties of earthquakes for earthquakes as small as possible (ideally down to M1 or below) in near-real-time. I also want to detect and analyse esoteric signals such as low-frequency earthquakes and tremor, again, in near-real-time.	Characterise background seismicity and changes therein around volcanic unrest periods to detect and assess changes in seismicity associated with faulting and volcanic processes.	• Dense broadband seismic networks around all main volcanic fields, ideally with station spacing <2 km, with good azimuthal coverage. • Broadband, low-noise data for tremor and low-frequency earthquake signals. • Telemetered data in near-real-time. • Consistent instrumentation to allow for correlation detection. • Well-known and constrained instrument response information to enable source characterisation.
Detect and accurately locate M1 and above earthquakes and calculate moment tensors / focal mechanisms.	Determine whether earthquake activity is related to tectonic faulting or magmatic activity by tracking earthquake propagation, depth and proximity to inferred magma chamber location and moment tensors.	• At least 10 stations. • Collecting short-period or broadband seismic data. • Within 20 km. • With complete azimuthal coverage around vent/volcano (no azimuthal gaps larger than 45°). • Of all volcanoes.
Detect and monitor the amount and amplitude of tremor/low-frequency energy.	Determine whether there is increased subsurface fluid movement (gas/hydrothermal/magma) at the volcano.	• At least three stations. • Collecting broadband seismic data. • Within 5 km of the vent/volcano. • Of all volcanoes.

I Want to:	So that I Can:	To Do this I Need:
Use the ambient noise field to continuously monitor for changes in seismic velocity.	Determine whether there are any sudden subsurface changes at the volcano that can indicate the migration of fluids and/or magma.	• At least two stations. • Collecting broadband seismic data. • Within 20 km and an inter-station path that intercepts the volcano. • Of all volcanoes.
Locate volcanic eruptions.	Give more precise volcanic hazard advice.	• 3–4 acoustic arrays with four air-pressure sensors each. • Collecting data at 100 Hz. • Within 15–20 km. • Of the Tongariro National Park volcanoes.
Locate sources of volcano-seismic signals such as volcanic tremor and very long period earthquakes.	Detect changes in the volcano's state before a potential eruption.	• 3–4 seismic arrays with four broadband, three-component seismic sensors each (could be co-located with air-pressure sensor arrays). • Collecting data at 100 Hz. • Within 15–20 km. • Of the Tongariro National Park volcanoes.
Use fibre-optic cables to detect volcanic earthquakes and strain variations.	Monitor variations on the volcanic activity in detail.	• One or more fibre-optic cables around the volcanic area of interest. • Data that are automatically collected, processed and analysed.
Quickly and accurately model sources of ground deformation.	Determine whether ground deformation is being caused by inflation/deflation from a volcanic source, which can indicate volcanic unrest and potential eruption.	• At least 10 stations. • Collecting ground deformation data (ideally three dimensions) with at least daily frequency. • Within 10 km, with at least one above the vent. • With complete azimuthal coverage around the vent/volcano (no azimuthal gaps larger than 45°). • Of all volcanoes.

I Want to:	So that I Can:	To Do this I Need:
Densify the network distribution in areas not effected by active volcano deformation.	Use these stations as stable reference sites to improve my GNSS solution.	• At least 4–6 stations installed around the volcanic area. • Installed at different azimuths. • Collecting the same datasets as the 'internal' stations. • Distance depends on volcano topography and tectonic signal in the area. • Of all volcanoes.
Detect the presence of ash in volcanic plumes.	Monitor for changes in eruptive activity.	• An array of stations around the volcano crater. • Collecting 1 second GNSS data. • Geometrically distributed around the crater. • Within 5 km. • Of all volcanoes.
Detect transient deformation signals using continuously collected GNSS data.	Monitor for changes in volcanic activity and constrain volumes of magma that are coming to the surface.	• An array of stations around the volcano crater. • At least three stations that can be used as 'reference' in an area away from the volcano that is not typically influenced by volcanic deformation. • Collecting 30 second GNSS data. • Producing sub-daily time series that are updated every hour. • Of all volcanoes.
To measure volcano vertical deformation via repeated levelling surveys.	Constrain vertical deformation with a geodetic technique that is not space-based and does not suffer by scale biases deriving from the satellite constellations.	• An established levelling network. • A levelling survey repeated at least once per year. • Benchmarks that are co-located with GNSS stations so that different geodetic techniques can be combined.
Measure mass fluxes within volcanoes.	Monitor the migration of fluids and determine the fluid type from its density.	• Repeated campaign gravity measurements in conjunction with deformation measurements at caldera volcanoes or volcanoes with deformation.

I Want to:	So that I Can:	To Do this I Need:
Detect changes in gas emission.	Monitor for changes in level of volcanic activity.	• Four stations. • Collecting 4–5 minutes SO_2 concentration during the day from DOAS. • Within 4 km. • Of all volcanoes.
Detect changes in gas emission.	Monitor for changes in SO_2 flux regime and detect when magma is closer to the surface.	• Four stations. • Collecting 0.5 Hz rate images of SO_2 concentration from a UV camera. • Within 5 km. • Of volcanoes emitting plume.
Continuously quantify the gas emissions (composition and flux) via plumes from a volcano.	Observe changes in the composition and flux of the gases being emitted from the volcano. These might indicate (1) magma movement in the sub-surface (e.g. recharge, ascent), (2) changes in the style of degassing in the magma reservoirs or (3) changes in the hydrothermal system (e.g. sealing). All of these may precede a phreatic and/or magmatic eruption. It can also help estimate the depth of magma in the sub-surface and the amount of interaction between the magmatic and hydrothermal systems.	• To quantify the SO_2 flux: - 3–4 stations per volcano. - Collecting atmospheric SO_2 concentration measurements (e.g. DOAS or UV camera) and wind speed/direction (together these can be processed to produce flux). - Within ~7 km of the crater (SO_2 and wind data should be co-located) in different directions so that measurements can be made regardless of wind direction. • To quantify the composition: - 3–4 stations. - Collecting atmospheric SO_2, H_2S and CO_2 concentration measurements (e.g. MultiGAS). - Around the crater edge in different directions so that measurements can be made regardless of wind direction. • At Tongariro, Ngauruhoe, Ruapehu, Whakaari and Raoul.

I Want to:	So that I Can:	To Do this I Need:
Periodically quantify the carbon isotope ratio of the volcanic plume.	Observe changes in the carbon isotope ratio of the gas being emitted from the volcano. This might indicate (1) magma movement in the sub-surface (e.g. recharge, ascent); or (2) changes in the style of degassing in the magma reservoirs, which may precede a magmatic eruption.	• Periodic collection of gas samples from the plume (e.g. tedlar bag flown into the plume using a drone or plane) for subsequent analysis in the lab. • Ruapehu and Whakaari plume (if plumes were detected elsewhere, these could be added).
Periodically quantify the composition of aerosols being emitted from the volcano.	Observe changes in the composition of the gas being emitted from the volcano. These might indicate (1) magma movement in the sub-surface (e.g. recharge, ascent), (2) changes in the style of degassing in the magma reservoirs or (3) changes in the hydrothermal system (e.g. sealing). All of these may precede a phreatic and/or magmatic eruption.	• Periodic collection of aerosol samples from the plume (e.g. cascade impactor and/or filter pack flown into the plume using a drone or plane) for subsequent analysis in the lab. • Ruapehu and Whakaari plume (if plumes were detected elsewhere, these could be added).
Quantify the CO_2 gas flux and its carbon isotope ratio being emitted to the atmosphere from volcanoes.	Observe changes in the composition of the gas being emitted from the volcano during eruption. These might indicate (1) magma movement in the sub-surface (e.g. recharge, ascent), (2) changes in the style of degassing in the magma reservoirs or (3) changes in the hydrothermal system (e.g. sealing). These may precede changes in volcanic activity during an eruption.	• Measurement of CO_2 flux from the soil or lake surface (e.g. gas accumulation chamber). • Periodic collection of gas samples being emitted from soil or lake surface (e.g. gas accumulated in the gas accumulation chamber sampled into a tedlar bag) for subsequent analysis in the lab. • Campaign mode over large areas (e.g. crater lakes or crater floors), e.g. Ruapehu and Whakaari, caldera areas (e.g. Ōkataina). • Potentially continuous in some caldera regions (e.g. Ōkataina).

I Want to:	So that I Can:	To Do this I Need:
Periodically measure the composition (concentration, speciation, e.g. CO_2, SO_2, H_2S, H_2, He, O_2, N_2, Ar, CH_4, NH_3, HCl, HF, HBr, hydrocarbons for gases and pH, Li, Na, K, Ca, Mg, Cl, SO_4, B, SiO_2, H_2S, Al, As, Br, F, Fe, NH_3 for water – isotope ratio – e.g. ^{2}H, ^{18}O, $^{13}C_2H_4$, $^{13}CO_2$, $^{2}H_2$,$^{15}N_2$, ^{13}CO, ^{34}S) of fluids (gases and waters) being released from fumaroles, springs, lakes and wells surrounding volcanic vents, calderas and geothermal areas.	Observe changes in the composition of the fluids released over time. These might indicate (1) magma movement in the subsurface (e.g. recharge, ascent), (2) changes in the style of degassing in the magma reservoirs or (3) changes in the hydrothermal system (e.g. sealing). These may precede a phreatic and/or magmatic eruption or indicate renewed activity in dormant areas. They can be used to understand the magmatic-hydrothermal interactions.	• Representative sites at all volcanoes, calderas and geothermal sites (e.g. current list of GeoNet features but, additionally, sites at Taranaki and future sites of interest as conditions change) – sampling frequency depends on Volcano Alert Level. • Collecting direct samples (CO flask, caustic flask, various water samples, condensates), which are subsequently analysed in the lab. • Ideally autonomously and remotely to enable more frequent measurements.
Continuously measure the temperature of fumaroles, springs, lakes and hot ground surrounding volcanic vents, calderas and geothermal areas.	Observe changes in the temperature of these features over time. These might indicate changes in the fluids reaching the surface, which may precede a phreatic and/or magmatic eruption or indicate renewed activity in dormant areas.	• Representative sites at all volcanoes, calderas and geothermal sites (e.g. current list of GeoNet features but additionally sites at Taranaki and future sites of interest as conditions change). • Collecting continuous temperature measurements (e.g. thermocouple – both in the feature and the air, or thermal imagery potentially).
Continuously measure the chemical composition of fumaroles surrounding volcanic vents.	Observe changes in the composition (CO_2, H_2S and SO_2) of the gases being emitted from the volcano. These might indicate (1) magma movement in the sub-surface (e.g. recharge, ascent), (2) changes in the style of degassing in the magma reservoirs or (3) changes in the hydrothermal system (e.g. sealing). All of these may precede a phreatic and/or magmatic eruption.	• Sites at selected fumaroles at each volcanic vent (Tongariro, Ngauruhoe, Raoul, Whakaari – I don't think there are options at Ruapehu or Taranaki currently). • Collecting continuous gas concentration measurements (e.g. MultiGAS for CO_2, H_2S and SO_2).
Quantify the composition of bulk rock samples emitted during an eruption (e.g. a lava flow, dome building eruption).	Know the composition of the material, quantify the physical properties (e.g. viscosity), understand where in the magma system it came from, whether it is similar to other eruptions, and understand future changes in the eruption.	• Collection and retrieval of bulk rock samples (e.g. by airborne platforms such as drones, helicopters or plane) for analysis in the lab.

I Want to:	So that I Can:	To Do this I Need:
Quantify the composition, size and shape of ash emitted from volcanoes during passive degassing and eruptions.	Know if juvenile material is being emitted; where the material is coming from in the sub-surface; whether it is similar to material that has been erupted previously; what the fragmentation mechanism is – these are related to what processes are driving the eruption, how the eruption might evolve in the future, where magma is being stored in the system and what the effects of the ash might have on agriculture.	• Collection and retrieval of ash samples (e.g. by airborne platforms such as drones, helicopters or planes or in stationary devices that are periodically collected). • Periodically when there is ash in a passive plume and in campaign mode during eruption.
Quantify the thickness of ash spatially.	Quantify the potential effects to communities, understand the scale of clean-up required, validate ash dispersion models that are key for predicting ash spread during the early stages of eruption.	Measurements of ash thickness around the volcano erupting.
Detect short- and long-term changes of the topography using high-resolution LiDAR data.	Monitor shallow landslides and rock falls (size and distribution) and track the long-term evolution of the volcanic topography. These datasets (currently missing) can also be used to estimate deposit thickness and volume from future eruptions (e.g. tephra, lava flow, debris avalanche, etc.).	Annual/repeated LiDAR acquisitions over National Park volcanoes.
Continuously observe the volcanic crater.	Relate changes in gas emissions (chemistry and flux) to activity occurring in the crater to understand what processes are driving changes in the gas emissions. Additionally, during eruption, seeing the style of eruption in order to understand the causes and potential impacts.	• 3–4 stations for [Volcano Alert] Level ≥1 volcanoes, 1–2 stations for Level 0 volcanoes. • Collecting visual and thermal images continuously (webcams). • Around the crater edge for Level ≥1 volcanoes.
Observe active lava flows and/or dome-building events during an eruption.	Quantify the speed, observe its behaviour and understand potential future behaviour to understand potential impacts.	• Collecting visual and thermal images from an airborne platform (e.g. helicopter or drone). • Campaign mode during an eruption.
Images that permit easy discrimination between ash and non-ash plumes.	-	Cameras appropriately sited to provide the necessary views to do this.

I Want to:	So that I Can:	To Do this I Need:
Better monitor temporary changes that existing cameras cannot see.	-	A temporary telemetered camera capability that can be deployed in response to monitoring needs. For new phenomena or short-term changes and features not visible by an existing camera; to prove/disprove a possible change.
Map heat distribution, repeatedly and frequently.	-	Thermal capable cameras, applied especially to areas where other technology is difficult to apply, where there are health and safety restrictions or where observations are required over a wide area (e.g. different parts of a lake or area of hot ground). Use different types of cameras, using different wavelengths of light.
Be able to see information in images taken at night more frequently than is currently possible.	-	Cameras with better night vision capability. Keep up with camera technology. Ensure we are using the most appropriate technology for our needs.
Get improved inputs to modelling by triangulating eruptions from more than one camera.	-	Camera views and image rate sufficient to capture adequate views of eruptions.
Better understand what is shown in an image. Currently the long time gap between images makes it difficult to understand some of what is shown in an image, e.g. the nature and possible movement of a 'cloud'.	-	A higher image rate.
Help MetService issue an initial advisory within 20 minutes of a reported eruption if a credible observation is available. Confirm/cancel that within 55 minutes.	-	Enough images, and reliable image collection, to provide a credible observation within 20 minutes of a reported eruption.
Better monitor visible changes involving small objects.	-	Higher image resolution in order to see smaller features more distinctly.

I Want to:	So that I Can:	To Do this I Need:
Track smaller objects (e.g. individual ballistics).	-	Higher image rate. Required rate depends on size of field of view and how fast items move through the view. Higher image resolution to see smaller objects.
Be able to download near-real-time continuous seismic, gas geochemistry, meteorological, levelling and temperature data from the within 1 km of active volcanic vents.	Operate models and online tools to quantify short-term eruption probability in real-time.	• At least one station of broadband type within 1–2 km distance of Whakaari vent, Ruapehu crater lake, possible vents on Tongariro and Taranaki. • One multi-gas sensor, permanently installed, at Whakaari vent and Ruapehu crater lake. • One webcam, permanently installed, trained on potentially active Whakaari vent and Ruapehu crater lake. • One temperature sensor installed on a Whakaari fumarole or Ruapehu crater lake.

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